INSTITUTE FOR CATASTROPHIC LOSS REDUCTION

A SPATIAL FUZZY COMPROMISE PROGRAMMING FOR MANAGEMENT OF NATURAL DISASTERS

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The Institute for Catastrophic Loss Reduction (ICLR) was established in 1998 with the mission to reduce the loss of life and property caused by severe weather and earthquakes through the identification and support of sustained actions to improve society's capacity to adapt to, anticipate, mitigate, withstand and recover from natural disasters.

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EXECUTIVE SUMMARY

Natural disasters affect regions with different intensity and produce damages that vary in space. Topographical features of the region; location of properties that may be exposed to the peril; level of exposure; impact of different mitigation measures; are all variables with considerable spatial variability. A new method for evaluation of disaster impacts has been presented in this report that takes into consideration spatial variability of variables involved and associated uncertainty. Flood management has been used to illustrate the utility of proposed approach.

Floodplain management is a spatial problem. Representation of flood damage mitigation alternatives and objectives in space provides a better insight into the management problem and its characteristics. Protection of a region from floods can be achieved through various structural and non-structural measures. Comparison of different measures and evaluation of their impacts is based on the multiple criteria. If they are described spatially, decision-making problem can be conceptualized as spatial multi criteria decision-making (MCDM). Tkach and Simonovic (1997) introduced spatial Compromise Programming (SPC) technique to account for spatial variability in flood management.

Some of the criteria and preferences of the stakeholders involved with flood management are subject to uncertainty that may originate in the data, knowledge of the domain or our ability to adequately describe the decision problem. The main characteristic of flood management is the existence of objective and subjective uncertainty. Fuzzy set theory has been successfully used to address both. Bender and Simonovic (2000) incorporated vagueness and imprecision as sources of uncertainty into multi criteria decision-making in water resources.

In this report a new technique named Spatial Fuzzy Compromise Programming (SFCP) has been developed to enhance our ability to address the issues related to uncertainties in spatial environment. A general fuzzy compromise programming technique, when made spatially distributed, proved to be a powerful and flexible addition to the list of techniques available for decision making where multiple criteria are used to judge multiple alternatives. All uncertain variables (subjective and objective) are modeled by way of fuzzy sets. In the present study, fuzzy measures have been introduced to spatial multi criteria decision-making in the GIS environment in order to account for uncertainties.

Through a case study of the Red River floodplain near the City of St. Adolphe in Manitoba, Canada, it has been illustrated that the new technique provides measurable improvement in flood management. Final results in the form of maps that shown spatial distribution of the impacts of mitigation measures on the region can be of great value to insurance industry.

Detailed project reports by Nirupama and Simonovic (2002) and Prodanovic (2001) are available on line at: http://www.engga.uwo.ca/research/iclr/fids/products.html

Keywords: Water resources, flood management, disaster mitigation, spatial compromise programming, multi-criteria decision making, spatial fuzzy multi objective analysis.

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INTRODUCTION

Natural disasters are spatially distributed phenomena. Their impacts have different characteristics at different locations within a region that may be affected. Damage caused by the natural disasters therefore, exhibits the same spatial variability. Knowledge of spatial variation of disaster impacts is of primary concern in understanding vulnerability and risks associated with property under disaster threat. Similarly, evaluation of protection effects of different disaster mitigation actions (structural and non-structural) could benefit from accurate knowledge of spatial distribution of disaster impacts. Floodplain management is used in this report to introduce an original approach to disaster decision making that takes into consideration a spatial distribution of variables and various associated uncertainties. Disaster decision making problem is formulated in this research as a multi criteria problem that involves multiple stakeholders.

Compromise Programming (Zeleny, 1973), a multi criteria decision making (MCDM) technique, is a powerful tool that can assist floodplain management in general. Applications of MCDM techniques to water resources have come a long way since the work of Maass et al. (1962) and Cohon and Marks (1973), where the decision problems were formulated as linear programming vector optimization problems. In order to address a particular flood management problem, typically decision makers are required to select and implement the best solution to the problem from a set of potential structural and non-structural alternatives. This process includes conflicting quantitative and qualitative criteria and multiple decision-makers. MCDM techniques help in evaluation and ranking of alternatives based on criteria values associated with each of the alternatives, and preferences of various decision makers towards the criteria.

Conventional MCDM techniques do not consider the spatial variability of the criteria values, which are used to evaluate potential alternatives. The criteria values, which they use, represent average or total impacts incurred across the entire region being considered. Thus in identifying the best solution from a set of potential flood mitigation alternatives using conventional MCDM techniques, only the region as a whole is considered. By doing so, the local variation in impacts resulting from the implementation of various flood protection alternatives is ignored. Consequently, the alternative identified as the best for an entire region by a conventional MCDM is rarely the best for all locations within that region.

Integration of Geographic Information System (GIS) with multi objective decision making techniques allows for incorporation of spatial dimension into the problem solving process. Many of the GIS systems are equipped with a graphical user interface, which increases the decision maker's comprehension of the spatial information. A GIS is often included as one of the major components in the development of the Decision Support Systems (DSS) (Simonovic, 1993, 1999; Walsh, 1993; Fürst el. al., 1993; Leipnik et. al., 1993; Watkins et. al., 1996; and Fedra, 1997).

Tkach and Simonovic (1997) addressed spatial variability in the criteria values associated with the various alternatives by combining the Compromise Programming (CP) with the GIS technology to develop a new technique named Spatial Compromise Programming (SCP). SCP can be efficiently used to generate, evaluate, and rank a set of potential flood protection alternatives taking into consideration spatial variation of main decision variables. The distance from the ideal solution for each alternative is measured by the distance metric. This value, which is calculated for each alternative and each location within the region, is a function of the criteria values themselves, the relative importance of the various criteria, and the importance of the maximum deviation from the ideal solution (Simonovic, 1989). The best compromise alternative, then, is determined by picking the largest distance metric values out of all the alternatives' for each location in the region. Presenting the best compromise solution for each location on the map allows an easy comprehension of spatial distribution of effects that different alternatives have on reducing the impact of natural disaster (in this case flooding).

Distance metric calculation (Tkach and Simonovic, 1997) is performed according to:

$$L_{j,x,y} = \left[\sum_{i=1}^{n} w_i^p \left| \frac{f_{i,w,x,y} - f_{i,j,x,y}}{f_{i,x,y}^{*} - f_{i,w,x,y}} \right|^p \right]^{1/p} \quad (1)$$

where: L_j is the distance metric; f_i^* is the optimal value of the i^{th} criteria; $f_{i,j}$ is the value of the i^{th} criteria for alternative j; $f_{i,w}$ is the worst value of i^{th} criteria; w_i are weights indicating decision maker preferences; p is a parameter ($1 \leq p \leq \infty$); $i = 1$, n criteria; $j = 1$, m alternatives; $x = 1$, a rows in the image; $y = 1$, b columns in the image; a is the number of rows in the image; and b is the number of columns in the image

Though SCP is capable of accounting for the spatial variability in main decision variables, it was unable to address various uncertainties associated with complex system of multiple alternatives, multiple criteria and multiple decision makers. Uncertainties in model assumptions, data, or parameter values, also contribute to the complexity of decision making process.

Disaster decision making formulated as a spatial multi criteria decision problem is subject to multiple sources of uncertainty. The main sources of uncertainty include input data, domain knowledge, human judgment, and others. Disaster decision making is a process that involves both, objective and subjective uncertainty. In order to deal with both types of uncertainty in the most efficient way a fuzzy set theory has been adopted in this research. Fuzzy decision making techniques can address vagueness and conflict of preferences common in group decision making (Blin, 1974; Siskos, 1982; Seo and Sakawa, 1985; Felix, 1994; and others), and at least one effort has been made to combine decision problems with both stochastic and fuzzy components (Munda et. al., 1995). Application, however, demands some level of intuitiveness for the decision makers, and encourages interaction or experimentation such as that found in Nishizaki and Seo (1994). Authors such as Leung (1982) and many others have explored fuzzy decision making environments. Fuzzy decision making process is not always intuitive to all people involved in practical decisions because the decision space may be some abstract measure of fuzziness, instead of a tangible measure of alternative performance. The alternatives to be evaluated are rarely fuzzy. Their performance is fuzzy. In other words, a fuzzy decision making environment may not be as generically relevant as a fuzzy evaluation of a decision making problem. The Fuzzy Compromise Programming (FCP) technique developed by Bender and Simonovic (2000) transforms a Compromise Programming distance metric into a fuzzy set by changing all inputs through the application of fuzzy extension principle. FCP approach can address various uncertainties that are associated with the natural hydrological processes occurring in flood management; data monitoring systems; equipment accuracy; and lack of knowledge. FCP approach ranks alternatives using fuzzy ranking measures designed to capture the effect of risk tolerance differences among decision makers (Prodanovic, 2001).

In this research floods are selected as an example of natural disasters. Contemporary flood management is characterized by a more integrated approach, including measures such as source control (watershed/landscape structure management), insurance, forecasting, warning and land use planning (Simonovic, 2002; Kundzewicz, 2002). Conventionally, most of the flood management is done without considering spatial heterogeneity and uncertainty involved (Bose and Bose, 1995). Flood management is a typical example of multi criteria decision problem. Examples of potential criteria are: minimization of the damage to human lives and property; minimization of the depth of floodwater in the inundated region; maximization of effectiveness of disaster emergency measures; and minimization of the emergency response time. Many flood protection measures, such as, water diversion and/or dike construction around a region have spatially varying flood control effects. Most of the criteria values, such as, floodwater depth and damages are also spatially variable. Spatial Compromise Programming (Tkach and Simonovic, 1997) can address spatial variability of decision variables.

There are numerous uncertainties associated with flood management. These uncertainties may arise from data monitoring systems; equipment accuracy; lack of understanding of physical processes involved; lack of knowledge; limitations of mathematical tools used to represent different physical processes; weights or preferences assigned to each of the criteria by the stakeholders; etc. Fuzzy Compromise Programming can address all kinds of uncertainties (Bender and Simonovic, 2000). However, there is no method available, to date, which can account for spatial variability in decision variables as well as uncertainties associated with flood management.

A new technique has been developed in this study (Nirupama and Simonovic, 2002), which is named the Spatial Fuzzy Compromise Programming (SFCP). This approach extends the Spatial Compromise Programming by transforming distance metric (equation 1) into a fuzzy set by changing all inputs through the application of fuzzy extension principle. The distance metric equation is now expressed as:

$$\tilde{L}_{j,x,y} = \left[\sum_{i=1}^{n} \tilde{w}_i^{\tilde{p}} \left| \frac{\tilde{f}_{i,w,x,y} - \tilde{f}_{i,j,x,y}}{\tilde{f}^*_{i,x,y} - \tilde{f}_{i,w,x,y}} \right|^{\tilde{p}} \right]^{1/\tilde{p}} \quad (2)$$

where: $\tilde{L}_{j,x,y}$ is the fuzzy distance metric; $\tilde{f}_{i,w,x,y}$ is the fuzzy worst value of i^{th} criteria; $\tilde{f}_{i,j,x,y}$ is the fuzzy value of the i^{th} criteria for alternative j; $\tilde{f}^*_{i,x,y}$ is the fuzzy optimal value of the i^{th} criteria; $\tilde{p}$ is a fuzzified parameter ($1 \le p \le$ ¥); $\tilde{w}_i$ are fuzzified weights indicating decision maker preferences; i = 1, n criteria; j = 1, m alternatives; x = 1, a rows in the image; y = 1, b columns in the image; a is the number of rows in the image; and b is the number of columns in the image.

Through a case study of the Red River Basin, Manitoba, Canada it has been successfully demonstrated that SFCP can, using a GIS environment, assist a decision maker in selecting the best flood protection alternative, taking into account the spatial variability of flood impacts, for each location (5 x 5 m grid) in the entire study region as well as accounting for the uncertainties involved in the process.

SPATIAL FUZZY COMPROMISE PROGRAMMING TECHNIQUE

This section presents the short description of the Spatial Fuzzy Compromise Programming (SFCP) technique. A detailed presentation of the technique, computational processes and data requirements are presented in the report by Nirupama and Simonovic (2002). Schematic presentation of the SFCP implementation process is shown in Figure 1. Initial data requirements include:

- Digital Elevation Model (DEM) of the region of interest;
- separate feature images of buildings, roads, agricultural fields and any other features, which might suffer damages in the region of interest;
- hydraulic data, including river reach cross section profile, expansion and contraction coefficients, Manning's n; and
- flood event data set.

Next step is to consider a set of potential flood protection alternatives that are feasible in the region of interest. Further, a set of relevant criteria/objectives needs to be decided upon. For example, in case of flood protection planning one of the criteria could be to minimize the depth of floodwater. Minimum damage to property and people is another potential criterion.

Having decided upon the criteria, a raster image is prepared for each of the criteria in which each raster cell contains the criteria values for all distinct geographic locations. This is accomplished using a combination of the flooded feature images, the water surface elevations as contained in the image, and the DEM of the region of interest. Raster cells in locations which were unaffected by floodwaters retain a value of zero. In this way an image containing the criteria values for all flooded locations in the study region can be produced for each alternative.

According to SCP technique, separate images showing the best and the worst criteria values for each location in the study region, are also necessary. Monetary value of damages to property and people can be estimated using appropriate relationships.

Criteria values associated with each of the alternatives are contained within sets of criteria images, which are georeferenced with the feature images. Therefore the total number of criteria images equals the product of the number of criteria and the number of alternatives. Each raster cell in a criteria image contains the criteria value for that geographic location associated with a particular alternative. If the criteria is spatially variable then each affected cell, or location, within the image has a different value. If the alternative impacts all locations within the region of interest equally, all impacted cells contain the same criteria value. Using GIS the spatial distribution of the criteria values are captured.

The best and the worst criteria values are also required for computation of the distance metrics. Once again, rather than having just a single value for each criteria, the best and the worst criteria values are determined for each location, or raster cell, in the feature image. This way each criterion has the best and the worst value image. The criteria values contained in the images, to be used for computation of the distance metrics, may be the actual or absolute minimum or absolute maximum. Choice of this is dependent on the criteria themselves and the opinion of the decision makers. If it is the actual extreme values that are desired, these may be determined by comparing the values of the individual criteria for each location, between the alternatives. The best and the worst value for each location can be extracted and placed into separate images using GIS commands. By using actual values, if the criteria values are spatially variable so too will be the best and the worst criteria value images. If the absolute maximum and minimum criteria values are required, new images georeferenced to the feature image are produced, whose initial value is that of the best or the worst criteria value.

Based on the criteria images, and the decision maker's preferences, a distance metric is produced for each alternative. Contained in the distance metric images are distance metric values for each impacted raster cell in the region of interest. As illustrated in Figure 1, the fuzzified distance metric values within the images are calculated by comparing impacts for each location on a cell by cell basis between all alternatives and

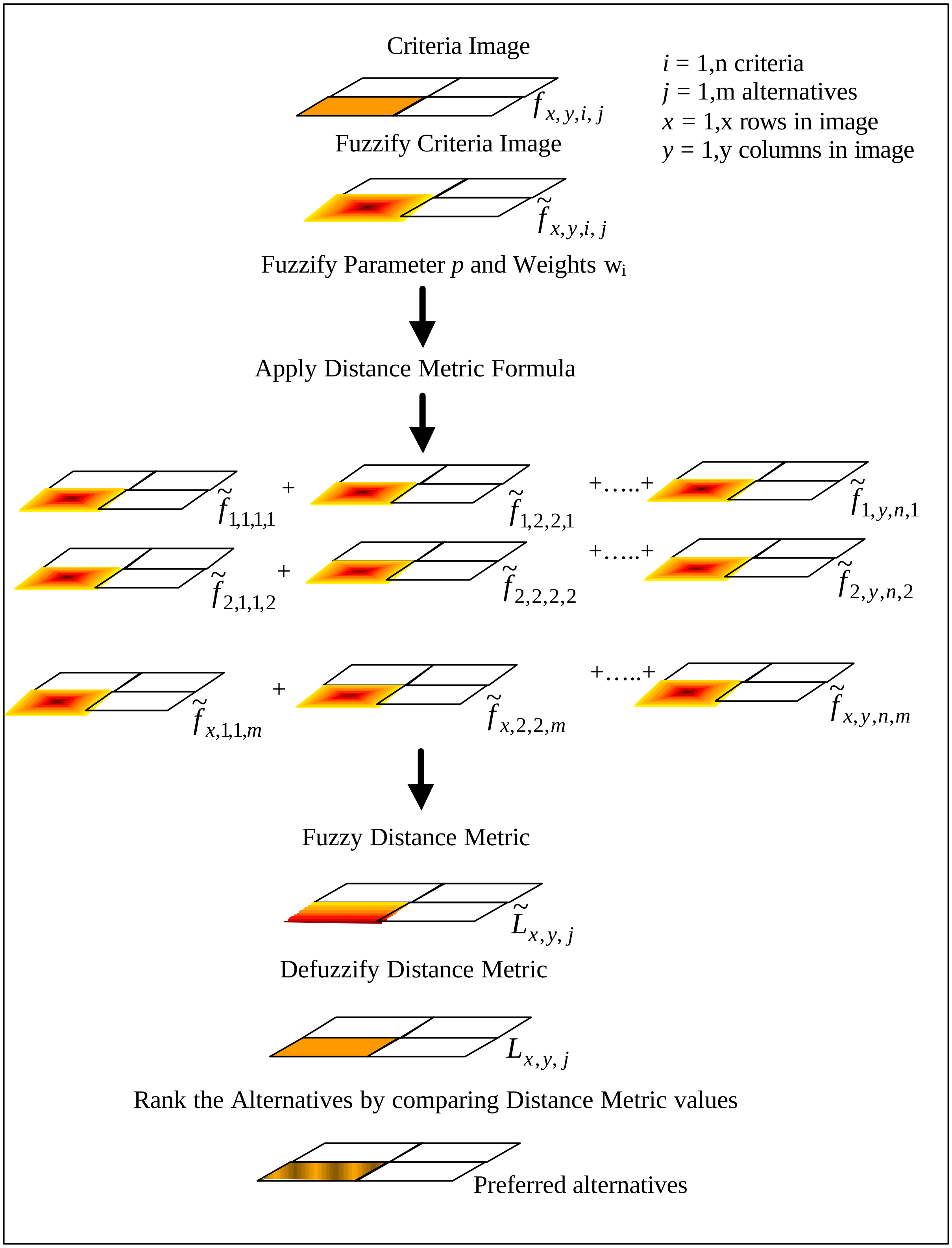

Figure 1: Schematic presentation of the Spatial Fuzzy Compromise Programming technique.

applying the decision makers' preferences, which are in a fuzzy form as well. All necessary computations are performed using GIS commands. Locations, or raster cells, in the study area for which there is no criteria value, or in other words, no impacts, are assigned a distance metric value of zero. Fuzzified distance metrics are then defuzzified for ranking purpose (Prodanovic, 2001; Prodanovic and Simonovic, 2002). Spatially variable ranking of flood protection alternatives is carried out to come up with the final picture of preference of each alternative for each location in the region of interest.

IMPLEMENTATION OF SFCP TO FLOOD DECISION MAKING – RED RIVER CASE STUDY

An example of flood disaster management in the Red River Basin, Manitoba is used to illustrate the proposed methodology. Triangular membership function has been chosen for fuzzification of variables for this particular application (Nirupama and Simonovic, 2002). All necessary computations are performed using GIS commands. Spatially variable ranking of flood protection alternatives is carried out to map preferred alternative for each location in the region of interest. The alternative having the largest distance metric value is selected as the best compromise solution.

Three flood protection alternatives that are considered in this study are: (i) dike around the St. Adolphe community (only at the right bank of the river); (ii) alteration of controlled floodway operation so as to let more floodwater flow through the floodway in order to protect the city of Winnipeg downstream. This was achieved by raising the floodway gate height in such a way that the water surface elevation at the floodway entrance was increased by 1 meter above the normal level. This alternative will be referred to herein as Floodway 1; and (iii) alteration of controlled floodway operation so as to let less floodwater flow through the floodway in order to protect the community of St. Adolphe upstream. This was achieved by lowering the floodway gate height in such a way that the water surface elevation at the floodway entrance was decreased by 1 meter below the normal level. This alternative will be referred to herein as Floodway 2.

Two criteria that exhibit a spatial variability are selected for evaluation of alternatives: (a) water depth; and (b) monetary value of flood damage. The computational procedures necessary to produce the raster criteria images involve the use of a GIS software and data on damage curves for buildings, agriculture and roads (Nirupama and Simonovic, 2002).

The first criterion used in the evaluation of the alternatives is the floodwater depth in the study region. An image is prepared in which each raster cell contained the water depth for all distinct geographic locations. This is accomplished using a combination of the flooded feature images, the water surface elevations as contained in the image, and the Digital Elevation Model (DEM) of the region. For all flooded areas, as indicated by the flooded feature image, the ground surface elevations in the DEM are subtracted from the simulated water surface elevation. Raster cells in locations which were unaffected by floodwaters retained a value of zero. In this way an image containing the water depth for all flooded locations in the study region was produced for each alternative.

KGS Group (2000) recommendations, which are based on 1997 flood event, are implemented to arrive at the monetary value of damages associated with each of the three categories considered in this study (damage to buildings, damage to roads and damage to agricultural fields).

Criteria values for the region of interest are decided upon and arrived at in a raster format with the help of Digital Elevation Model (DEM) and the feature images of buildings, roads and agricultural fields in GIS environment (Idrisi32, 2001). Potential flood protection alternatives are being simulated using hydraulic model HEC-RAS (Hydrologic Engineering Center, 2001) that works on GIS platform.

ILLUSTRATIVE RESULTS OF THE SFCP APPLICATION

Proposed SFCP has been implemented to all the three alternatives and for three weight sets representing different combination of stakeholders' preferences. In this research use of various shapes of fuzzy membership functions have been tested too. According to Equation (2), fuzzified distance metric images of the best scenario, the worst scenario and the actual criteria are obtained using (i) triangular membership function, and (ii) Z-shaped membership function. Special computational routines are developed to carry out the fuzzification of input criteria images as well as the fuzzified distance metrics calculation for each of the alternatives. Both triangular and Z-shaped membership functions are applied to the same set of input criteria images for the purpose of comparison. Implementation of SCP has also been carried out in this study to obtain deterministic distance metric images using Equation (1). Weights assigned to criteria values are chosen according to Table 1.

Table 1: Weights w_i indicating decision-maker preferences

Criteria	Decision-Maker's Preferences (w_i)		
	Weight Set # 1	Weight Set # 2	Weight Set # 3
Flood water depth	0.5	0.1	0.9
Damages	0.5	0.9	0.1

Implementation of SCP and SFCP produced distance metric images and final ranking of alternatives for all the three sets of weights assigned to the criteria values separately. This enables us to compare the performance of SCP, SFCP with triangular membership and SFCP with Z-shaped membership. Not necessarily all the inputs in distance metric equation need to be fuzzified. Some of the inputs about which reliability and accuracy is not an issue can be used in their crisp form, while fuzzy representation can be applied to others. Different membership function shapes can be applied to different inputs as well. The results obtained from this research are numerous and are all included in the report by Nirupama and Simonovic (2002).

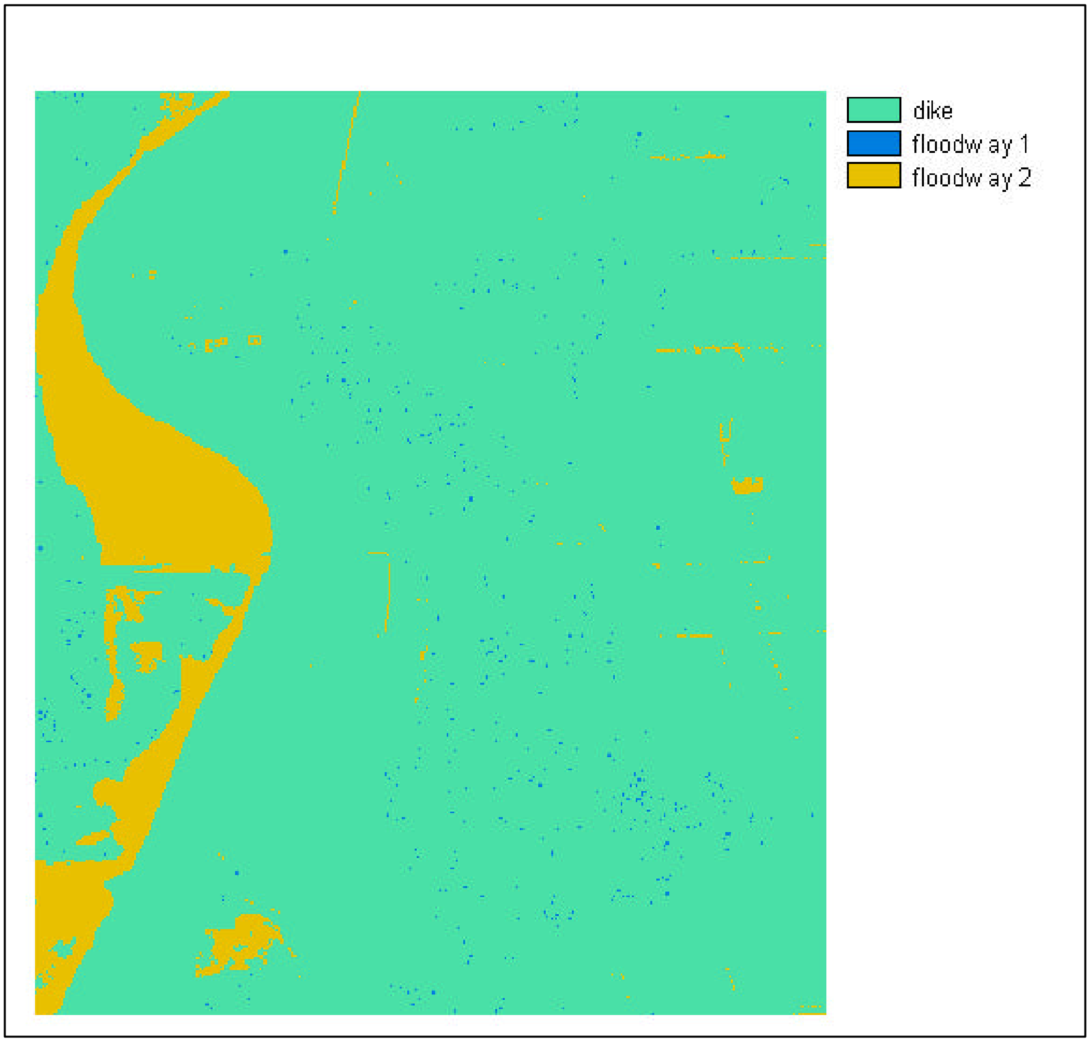

Figure 2: Spatially distributed ranking of alternatives using SCP analysis.

In this report only some of the final results are presented in Figures 2, 3 and 4 to illustrate the advantages of newly developed technique, SFCP. Figure 2 illustrates the spatial distribution of preferred flood protection alternatives using Spatial Compromise Programming analysis. SCP accounts for only spatial variability and not for uncertainties associated with disaster management, in general, and flood management in this particular example. It can be noted that flood protection alternative 'Dike' (shown in green) has been preferred in most of the study region except for the left bank of the Red River. Alternative 'Floodway 1' is seen to be providing protection to some scattered locations in blue. Alternative ‘Floodway 2’ (shown in yellow) is found to provide better protection to left riverbank of the Red River.

The spatial distribution of preferred flood protection alternatives is illustrated in Figure 3 using SFCP and triangular membership function. Flood protection alternative ‘Floodway 1’ can be seen to be most effective for the most of the study region in this case. Alternative ‘Floodway 2’ is preferred in some areas surrounding riverbanks and some residential areas plus few roads and agricultural fields (shown in yellow). Alternative ‘Dike’ is not seen to be providing much protection in comparison with other two flood protection alternatives.

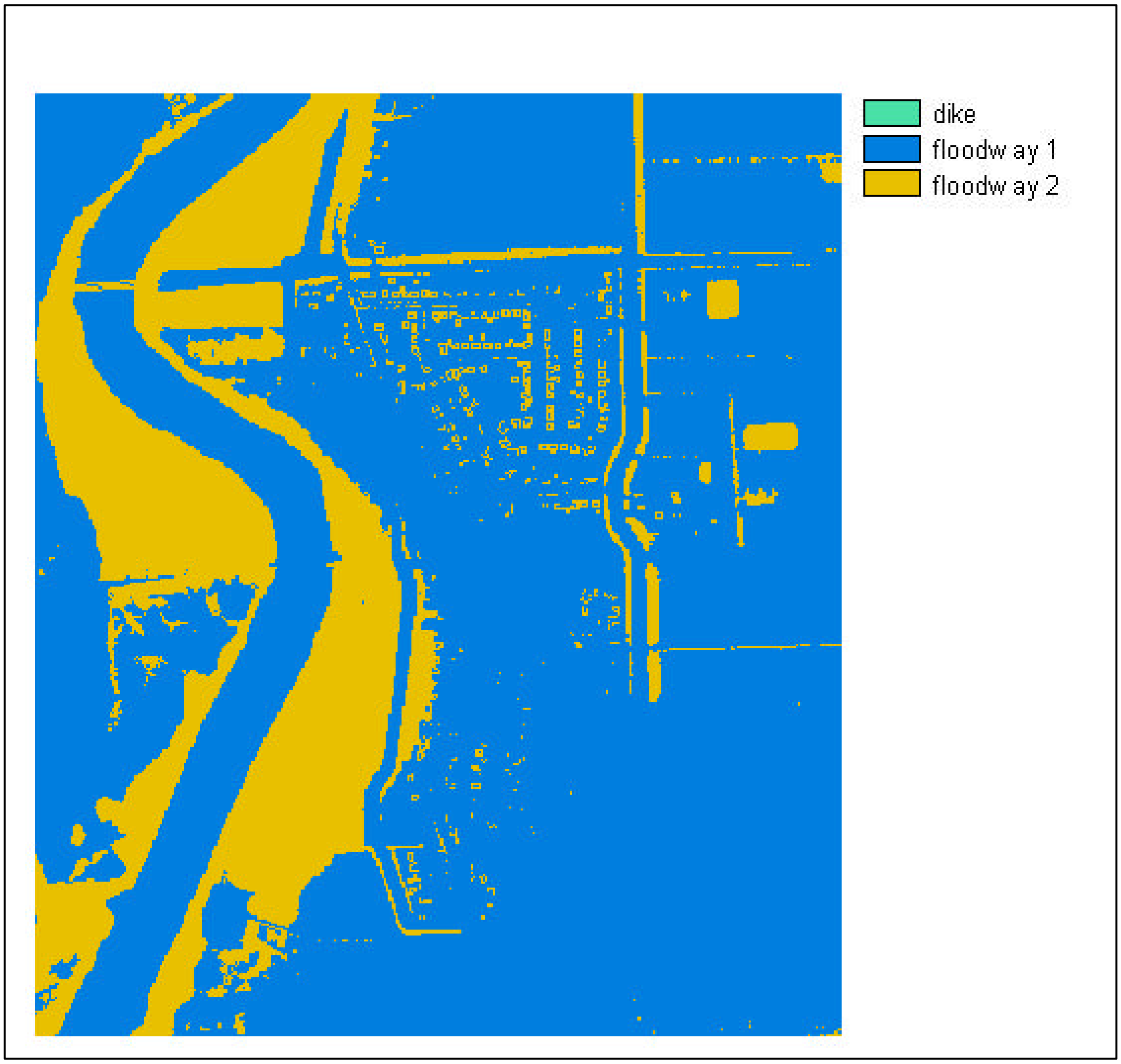

Figure 3: Spatially distributed ranking of alternatives using SFCP analysis.

Comparison of the two images in Figures 2 and 3 shows that when spatial variability in decision variables is combined with uncertainty involved the final results look quite different. We are concluding that the new technique developed in this research is increasing our ability to properly capture the disaster decision making processes which are exhibiting spatial variation in decision variables and are subject to numerous subjective and objective uncertainties.

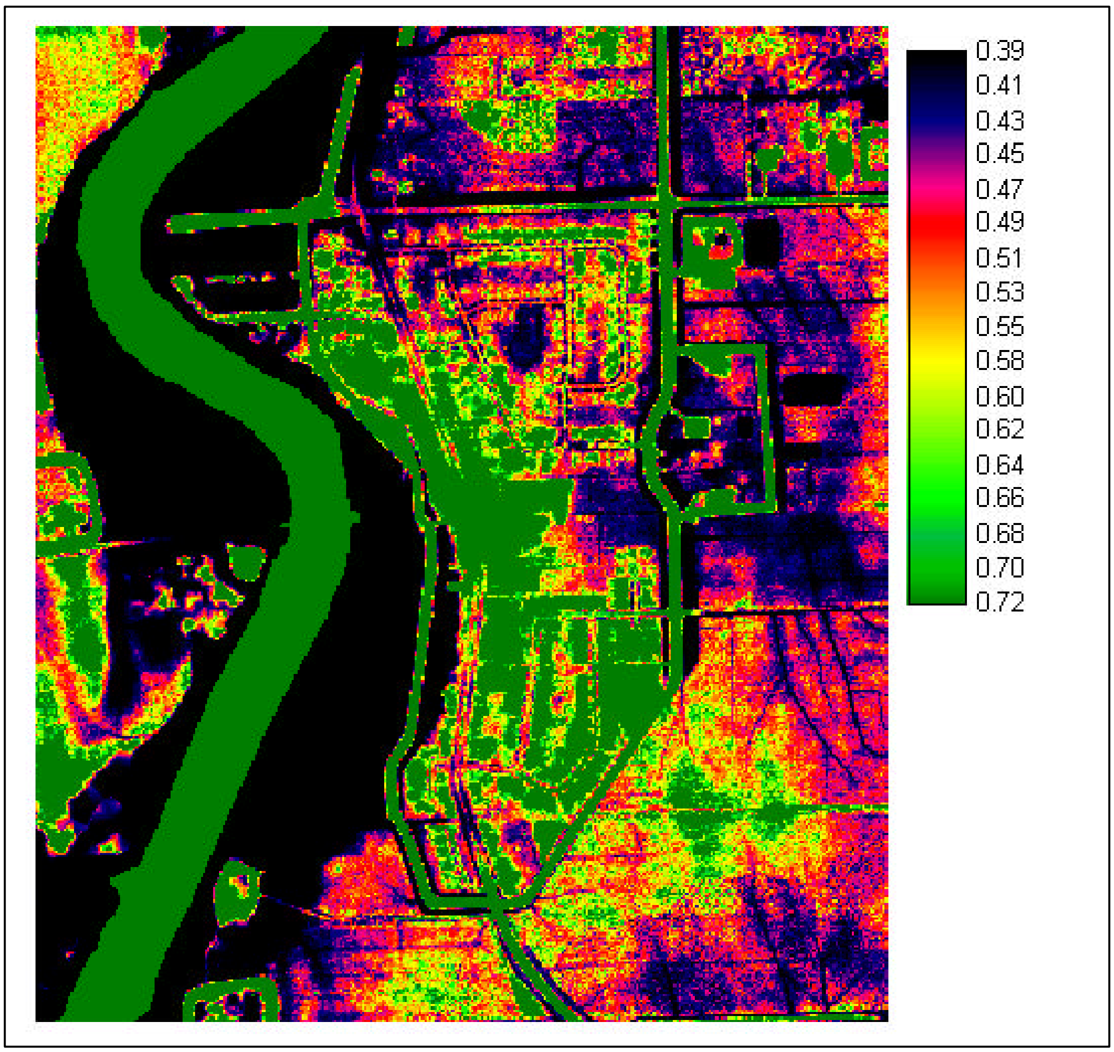

Figure 4: Distance metric image for alternative ‘Floodway 1’ using SFCP and Z-shaped membership.

In Figure 4 we selected to show an example of an image containing values of distance metric (Equation 2) obtained by implementation of alternative ‘Floodway 1’ using SFCP with Z-shaped membership function. Higher values of distance metric are considered to be better, which means that all the higher value regions are being protected by this particular flood protection alternative (‘Floodway 1’ in case of Figure 4). Such distance metric images are obtained for all the potential alternatives and compared during the ranking process. Highest distance metric value among all compared alternatives is being chosen on a cell by cell basis. For example images captured in Figures 2 and 3 are obtained after comparing three distance metric images for each flood protection alternative for highest value of distance metric in each cell in the study region. Please note that Figures 2, 3 and 4 are the cases of equal preference (Weight Set # 1 in Table 1) given to both criteria considered in this example of flood management.

UTILITY OF THE RESEARCH RESULTS TO INSURANCE INDUSTRY

Insurance industry relies heavily on future scenarios related to natural disasters that might occur and cause damage to human lives and property. Their interest lies in understanding the impact of natural disaster on insured property. This research provides the insurance industry with a powerful tool that will help evaluate complex impacts that a disaster might have over a region. With the help of the proposed method of Spatial Fuzzy Compromise Programming (SFCP), comparison of various protection options and their impact can be evaluated and visualized in space.

Through a case study of evaluation of flood protection alternatives this research has shown that integration of GIS, hydraulic modeling and fuzzy set theory provides vital means to evaluate the impact of flooding in space. In other words the level of exposure for any point in the region of interest is clearly visible. The depth of flooding and damage caused by a flood event can be determined spatially and the impact of various flood protection alternatives (structural and non-structural) can be assessed directly. Proposed technique can accommodate various choices of evaluation criteria as well as the stakeholders' preferences towards them. SFCP accounts for uncertainties associated with criteria values and decision maker's preferences. This will be of assistance to insurance industry in assessing risks and vulnerability when setting the insurance rates. SFCP facilitates ability to account for spatial variability of impacts. This is an additional benefit to insurance industry when dealing with natural disasters and their impacts over the large regions. Addressing spatial variability and uncertainties together has not been done before.

Final product of this research provides graphical representation of impacts for each of the alternatives considered, therefore, providing to insurance decision makers additional information that may assist them in evaluating the effects of disaster mitigation measures with more confidence, efficiency and accuracy. SFCP provides a very clear assessment of risk of exposure to natural disasters and the effect different protection options may have at different locations, subject to uncertainties involved.

CONCLUSIONS

There are various methods available that are in practice for assessing and evaluating disaster mitigation measures in general. Natural disasters are spatial phenomena that are complex in nature. Among the available methods some have the capability to address spatial variability and some can account for uncertainties associated with representation of such natural phenomena. In this research a new method called Spatial Fuzzy Compromise Programming (SFCP) has been developed and implemented that facilitates ability to address spatial variability in decision variables as well as uncertainties associated with multi criteria decision making process simultaneously. In multi criteria decision making stakeholders are many who would like their opinion to be included in the decision making process. SFCP has the ability not only to account for stakeholders opinion but also to address the uncertainties associated with preferences given to various criteria values by them. SFCP also allows flexibility in the process of accounting for uncertainties that may come from data involved; data monitoring equipment; and/or criteria values. Integration of GIS and fuzzy set theory provides this vital tool, which can deal with spatial variations and uncertainties altogether.

An example of flood control management is used in this research to illustrate the proposed SFCP analysis procedure and its capabilities. From decision making point of view it is clear in the example study that SFCP can be of value to insurance industry in the process of establishing different insurance policies for different locations in the region. Insurance decisions rely on accurate assessment of risk of exposure to natural disaster of the insured property. SFCP technique provides this information in space. Uncertainties that may affect this information are accounted for in SFCP analysis.

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